Prototype 3D Real-Time Imaging System Based on a Sparse PZT Spiral Array

 DOI: 10.1109/ULTSYM.2018.8580133

Prototype 3D real-time imaging system based on a sparse PZT spiral array

Enrico Boni
Department of Information Engineering
University of Florence
Florence, Italy
enrico.boni@unifi.it

Alessandro Ramalli
Department of Information Engineering
University of Florence
Florence, Italy
Lab. on Cardiovascular Imaging & Dynamics, Dept. of Cardiovascular Sciences
KU Leuven
Leuven, Belgium

Verya Daeichin
Acoustical Wavefield Imaging, ImPhys,
Delft University of Technology
Delft, the Netherlands

Nico de Jong
Acoustical Wavefield Imaging, ImPhys,
Delft University of Technology
Delft, the Netherlands
Biomedical Engineering, Thorax Center
Erasmus MC
Rotterdam, the Netherlands

Hendrik J. Vos
Acoustical Wavefield Imaging, ImPhys,
Delft University of Technology
Delft, the Netherlands
Biomedical Engineering, Thorax Center
Erasmus MC
Rotterdam, the Netherlands

Piero Tortoli
Department of Information Engineering
University of Florence
Florence, Italy

***Abstract*—3D ultrasound imaging is costly and complicated mostly due to the need of controlling 2D probes with high numbers of elements (⩾1024). Sparse arrays are a convenient way to reduce system complexity maintaining reasonable performance. A 256-element density tapered spiral array has been recently designed and realized in a piezoelectric probe prototype. The probe has been connected to the ULA-OP 256 open scanner, which can be programmed to permit volumetric scanning in real-time. This paper reports on the first experimental measurements of transmit ultrasound fields produced by such prototype system, including multi-line transmit fields that, in combination with parallel receive beamforming, may permit real-time volumetric imaging. An average -21.3dB side-lobe level (SLL) was measured on the transmit fields, while volume rates of 35 volumes per second can be achieved.**

Keywords—volumetric ultrasound, probe, sparse, multi-line transmit

I. INTRODUCTION

Nowadays, ultrasound research is widely dedicated to the development of 3D imaging methods and systems. However, the extension from 2D to 3D implies a tremendous increase in system complexity. This is especially true for channel count, since a simple 2D to 3D extension of standard imaging modes would yield systems and probes with thousands of active channels.

Experimental tests of novel 3D imaging methods are hardly feasible with machines intended for the general market, while they can be performed with special research systems [1]–[5]. These systems can now work with up to 1024 channels, but further extension of this number is not foreseen considering the corresponding probe cable size that would be needed.

A. Ramalli was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 786027 (ACOUSTIC project).

Sparse arrays, characterized by a limited number of elements "sparsely" distributed over the available aperture, are optimal candidates to reduce the system complexity, provided they maintain reasonable imaging performance [6], [7]. This goal may be achieved by properly designing the elements distribution according to deterministic or non-deterministic criteria [8]. The former includes arrays having a geometry based on a spiral pattern [9]. This approach, which is applied here for the first time to a piezoelectric probe, can be used for CMUT arrays as well [10].

This paper reports the experimental results of a 3D prototype system composed by a novel piezoelectric spiral array connected to the ULA-OP 256 open scanner. Section II introduces the methodologies used to perform the tests, Sec. III reports the results and related discussion, while conclusions can be found in Sec. IV.

II. METHODS

A. *Probe construction and integration with the ULA-OP 256*

The probe [11] was built with PZT-on-PCB technology in which the distribution of the 256 elements was based on a density tapered spiral [9]. The original random element positions of [9] were snapped onto a 220x220 μm grid to enable conventional transducer dicing in the production phase. The aperture diameter was 16 mm and working frequency was 5.5 MHz. All elements were directly wired to the probe connector cable, thus having full control in transmission and reception by the ULA-OP 256 open scanner [2]. To overcome cable attenuation due to the limited element surface, the receive signals are amplified and buffered by MAX4805 high-voltage-protected OpAmps (MAXIM Integrated, San Jose, CA) mounted on

TABLE I. PRESSURE FIELD MEASUREMENTS RESULTS AND COMPARISON WITH SIMULATION

Parameter	**TX Set**									
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
Steering angle, Azimuth [deg]	0	8	16	0	8	16	0	8	16	+16/-16
Steering angle, Elevation [deg]	0	0	0	8	8	8	16	16	16	+16/-16
Measured SLL [dB]	-25.3	-21.7	-18.7	-25.5	-22.8	-18.7	-20.7	-20.3	-18.2	-
Simulated SLL [dB]	-25.7	-24.5	-25.2	-24.9	-24.1	-23.8	-23.2	-23.4	-22.5	-
Measured Lateral resolution [mm]	0.93	0.93	0.95	0.93	0.95	1.00	0.98	1	1.03	1.45
Simulated Lateral resolution [mm]	0.85	0.83	0.85	0.83	0.85	0.85	0.85	0.85	0.85	1.25

custom designed regular PCBs, tightly coupled to the probe elements.

B. One-way field measurements

To evaluate the performance of the probe coupled with the ULA-OP 256 system, a series of one-way field measurements were performed. The ULA-OP 256 was configured to drive the 256 probe elements with 5 MHz, 3-cycle sinusoidal bursts at 40 Vpp. The ultrasound beams were focused at 20 mm with 9 different steering angle configurations, uniformly spaced between 0° and 16° in both elevation and azimuth planes (Table I). An additional configuration, exploiting the linear high-power transmitters allowed the multi-line transmission of 4 concurrent beams (4MLT) [12] .For each transmit (TX) configuration, a 3D acoustic scanning system was used to measure the emitted pressure field. The system was equipped with a lipstick hydrophone (HGL-0400, Onda Corp.) and synchronized with the ULA-OP 256 operations. The measured volume had dimensions of 20×20×20 mm^3, sampled with a resolution of 0.2×0.2×1 mm (along X, Y and Z direction, respectively) and centered at the focal point of the straight-transmit configuration (TX Set #1 in Table I). For each measuring point, the scanning system recorded the local pressure, and the maximum temporal value was then extracted. For each set the side-lobe level (SLL) and lateral resolution were evaluated and compared to the results obtained by Field II simulations of the same setup [13]–[15].

C. Wire phantom setup

The ULA-OP 256 system was programmed to scan a 60°×60° region of interest by means of 3600 focused scanlines using the spiral array. The operating software was configured to show in real-time two cross planes extracted from the fully beamformed volume. The probe was equipped with the MAX4805 preamplifier boards. The ULA-OP 256 system was programmed to directly provide the required high and low voltage power supplies to the pre-amplifiers. A wire phantom composed by 5 parallel 0.1 mm nylon wires spaced by 5 mm was investigated to assess axial and lateral resolution.

D. High frame-rate Setup

The ULA-OP 256 embeds a parallel multi-line beamformer [16], which allows to generate in real-time multiple scanlines for each transmission event. Using the settings of Sec. II.C, the system was configured to beamform 16 scanlines for each emission event. The maximum achievable Pulse Repetition Frequency (PRF) was measured.

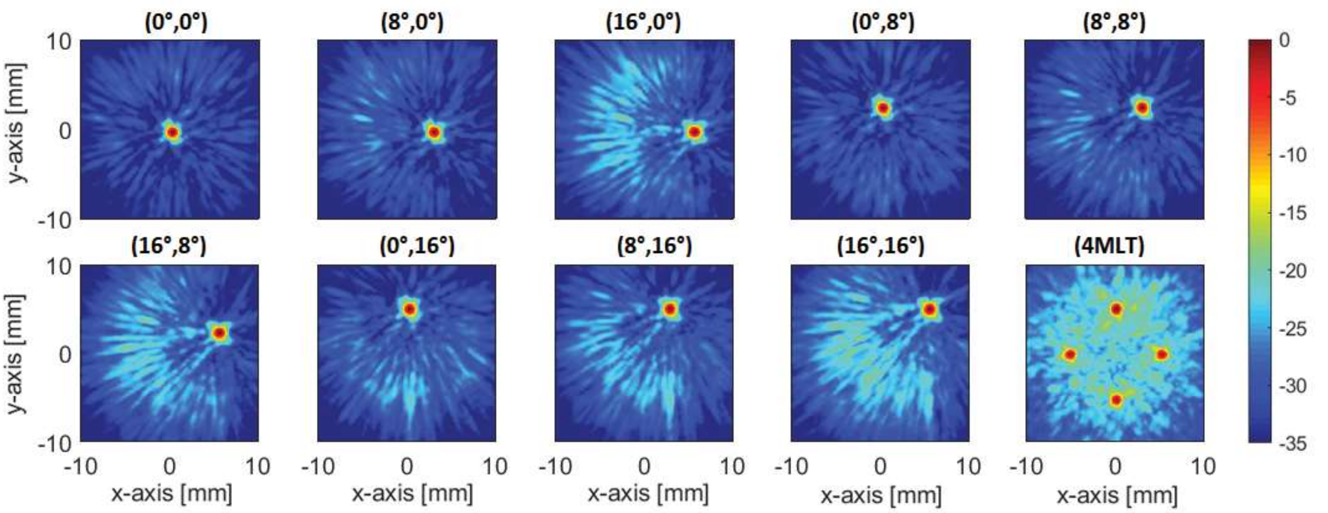

Fig. 1. C-scans of radiated pressure fields, taken at the focal depth, under different steering conditions. Each panel is normalized to its maximum value. The dynamic range is 35dB

III. RESULTS AND DISCUSSION

A. One Way fields

Figure 1 shows the C-Scans of the 10 sets taken at the focal depth. Table I reports the measured and simulated SLL and lateral resolution.

The differences between simulations and acquisitions can be partially explained by the non-ideal pulse response of this prototype. In fact, the piezoelectric material is directly bonded to a 1.6 mm thick PCB which, besides routing the signals to the connectors, also acts as a backing substrate, whose acoustic parameters are not optimized. Moreover, there was an element-to-element variation of ±3 dB in pulse-echo, and about 5% of all probe channels were not acoustically active.

B. Wire phantom results

A cross-plane image of the wire phantom is presented in Figure 2. Baseband beamformed data were saved and used in post-processing to evaluate the lateral and axial resolution which resulted 1.2 mm 1.2 mm respectively. Here again, the non-optimal acoustical parameters can explain the relatively poor resolution.

C. High frame-rate volume scanning

When beamforming in real-time 16 scanlines for each transmission event, the system was able to run at an 8kHz PRF. This implies that a 3600-scan-line volume can be reconstructed in real-time at 35 volumes per second. The volume could be scanned, for example, using a 4MLT-4MLA configuration, where 4 adjacent scanlines are beamformed for each one of the 4 transmitted beams.

IV. CONCLUSION

The prototype 3D system formed by the 256-element piezoelectric spiral probe and the ULA-OP 256 open scanner has been preliminarily tested. The system can produce a live volume rate of 35 frames per second. Although the imaging performance is still below the simulation results, these preliminary results show that the prototype system can act as a platform to further develop high frame rate imaging with spiral probes.

ACKNOWLEDGMENT

The authors wish to thank Marco Montagni for the help in developing the 3D-printed fixture for wire phantom tests.

REFERENCES

[1] E. Boni, A. C. H. Yu, S. Freear, J. A. Jensen, and P. Tortoli, "Ultrasound Open Platforms for Next-Generation Imaging Technique Development," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 65, no. 7, pp. 1078–1092, Jul. 2018.

[2] E. Boni *et al.*, "ULA-OP 256: A 256-Channel Open Scanner for Development and Real-Time Implementation of New Ultrasound Methods," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 63, no. 10, pp. 1488–1495, Oct. 2016.

[3] Verasonics Inc., "Vantage family brochure," Aug-2016. [Online]. Available: http://verasonics.com/wp-content/uploads/2016/10/Vantage_family_brochure_spec_sheet_-Aug2016.pdf. [Accessed: 06-Dec-2016].

[4] J. A. Jensen *et al.*, "SARUS: A synthetic aperture real-time ultrasound system," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 60, no. 9, pp. 1838–1852, Sep. 2013.

[5] L. Petrusca *et al.*, "Fast Volumetric Ultrasound B-Mode and Doppler Imaging with a New High-Channels Density Platform for Advanced 4D Cardiac Imaging/Therapy," *Appl. Sci.*, vol. 8, no. 2, p. 200, Jan. 2018.

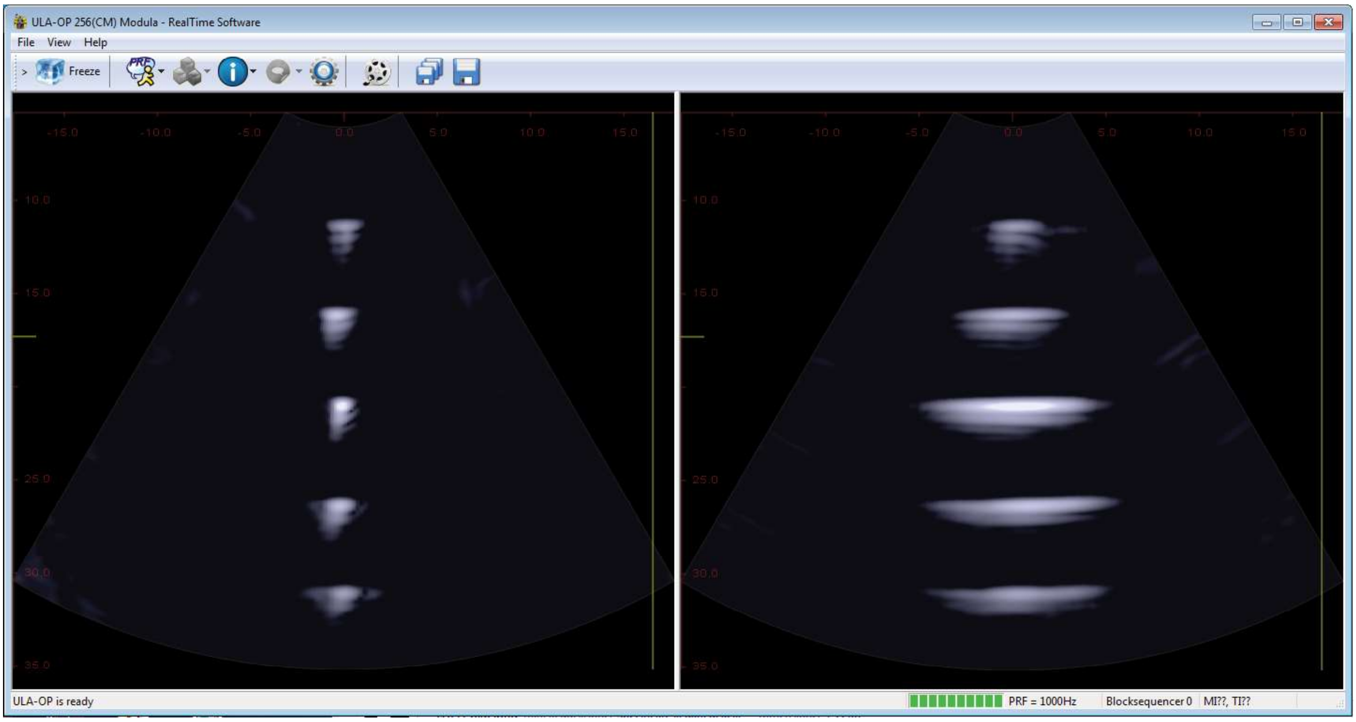

Fig. 2. ULA-OP 256 real-time software showing two cross planes of the wire phantom.

[6] E. Roux, F. Varray, L. Petrusca, C. Cachard, P. Tortoli, and H. Liebgott, "Experimental 3-D Ultrasound Imaging with 2-D Sparse Arrays using Focused and Diverging Waves," *Sci. Rep.*, vol. 8, no. 1, p. 9108, Jun. 2018.

[7] B. Diarra, M. Robini, P. Tortoli, C. Cachard, and H. Liebgott, "Design of Optimal 2-D Nongrid Sparse Arrays for Medical Ultrasound," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 11, pp. 3093–3102, Nov. 2013.

[8] E. Roux, A. Ramalli, P. Tortoli, C. Cachard, M. C. Robini, and H. Liebgott, "2-D ultrasound sparse arrays multidepth radiatio optimization using simulated annealing and spiral-array inspired energy functions," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 63, no. 12, pp. 2138–2149, 2016.

[9] A. Ramalli, E. Boni, A. S. Savoia, and P. Tortoli, "Density-tapered spiral arrays for ultrasound 3-D imaging," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 62, no. 8, pp. 1580–1588, Aug. 2015.

[10] A. S. Savoia *et al.*, "A 3D packaging technology for acoustically optimized integration of 2D CMUT arrays and front end circuits," in *2017 IEEE International Ultrasonics Symposium (IUS)*, 2017, pp. 1–4.

[11] H. J. Vos *et al.*, "Sparse volumetric PZT array with density tapering," in *2018 IEEE International Ultrasonics Symposium (IUS)*, 2018, pp. 1–4.

[12] L. Tong, A. Ramalli, R. Jasaityte, P. Tortoli, and J. D'hooge, "Multi-Transmit Beam Forming for Fast Cardiac Imaging: Experimental Validation and In Vivo Application," *IEEE Trans. Med. Imaging*, vol. 33, no. 6, pp. 1205–1219, Jun. 2014.

[13] J. A. Jensen, "FIELD: a program for simulating ultrasound system," *Med Biol Eng Comput*, vol. 34, no. Supp-1, Part 1, pp. 351–353, 1996.

[14] E. Maione, P. Tortoli, G. Lypacewicz, A. Nowicki, and J. M. Reid, "PSpice modelling of ultrasound transducers: comparison of software models to experiment," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 46, no. 2, pp. 399–406, Mar. 1999.

[15] J. A. Jensen and N. B. Svendsen, "Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 39, no. 2, pp. 262–267, Mar. 1992.

[16] E. Boni *et al.*, "Architecture of an Ultrasound System for Continuous Real-Time High Frame Rate Imaging," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 64, no. 9, pp. 1276–1284, Sep. 2017.